Modeling and Control of 2-DOF Underwater Planar Manipulator

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Abstract

This paper investigates the performance of the fuzzy model reference adaptive control applied on 2-dof underwater planar manipulator (MIMO system). Takagi-Sugeno fuzzification is chosen for the fuzzy system. Proportional-integral update law is used in the adjustment mechanism to obtain a fast parameters adaption. The focus of this paper is the study of the proposed controller performance in response to controlling the manipulator with the added terms in the dynamic equation ie. hydrodynamic effects contributed by ocean drift. The performance of the controller is analyzed in terms of servo tracking at each of the manipulator joints in the presence of hydrodynamic and hydrostatic effects of sea water.

Introduction

For the past decades, most of the research works on underwater manipulators (attached on the underwater vehicles-manipulator system (UVMS)) are centered on the study of its dynamics and modeling, mechanical development and control strategies [1-5]. These underwater mechanical manipulators are used for various unmanned/manned underwater missions such as pipeline inspection, coral reefs exploration and ship hull inspection, to name a few. From the survey that has been made by Yuh, many remotely operate vehicles (ROVs) are equipped with one or two manipulators and most autonomous underwater vehicles (AUVs) do not have any and are limited to survey-type application. Most of the commercial underwater manipulators such as Predator, Titan III S and The Arm-66 are designed with grippers as the end-effector [6]. Differ from the industrial or land-based manipulators, it is very challenging to control underwater manipulator due to some factors such as highly nonlinear, time-variant, uncertainties in hydrodynamic effects, disturbances by ocean currents and changes in the centers of gravity and buoyancy due to the motion. Therefore, it is difficult to fine-tune gain of a controller. Several advanced control systems have been proposed previously either for the underwater manipulator alone or coupled with the vehicles such as nonlinear feedback control (T.J. Tarn and S.P Yang, 1997), hybrid position/force control (Lionel et al, 1998), adaptive control (Pan-Mook Lee et al, 2000), and sliding control (Bin Xu and Shunmugham R. Pandian et al, 2006). The focus of this paper is on the adding of hydrodynamic effects into the dynamic equations and suggesting an effective control scheme to control its motion and ensure the stability whenever external disturbance and inputs variations occur.

In this paper, fuzzy model reference adaptive control (FMRAC) will be proposed. Previously, the effectiveness of adaptive fuzzy control has been proven for some nonlinear systems including for the land-based manipulator. To date, not much of the research works are done on applying the control scheme on the underwater manipulator. The advantage of fuzzy adaptive control is both numerical and qualitative information is used during construction and training stages [8]. It can estimate a function without requiring a mathematical description of how the output functionally depends on the input; it learns from samples. Fuzzy control can be a universal approximator on a compact space [9]. However fuzzy control alone cannot determine the stability of the system. Thus, model reference adaptive control (MRAC) scheme (direct or indirect adaptive control) seems to be the best approach for the implementation with the fuzzy control system since the stability robustness of the system can be analyzed via Lyapunov stability theory [10]. MRAC itself also has demonstrated its capabilities in many interesting nonlinear applications. The objective of MRAC is to design an adaptive controller such that the behavior of the controlled plant follows exactly with the behavior of a desirable model despite uncertainties or variations in the plant parameters. This means that the desired performance of the closed loop system is specified through a reference model and the adaptive system attempt to make the output of the plant follow the output of the reference automatically. A Takagi Sugeno fuzzy controller is used and directly tuned to achieve the reference model tracking performance. The fuzzy controller parameters are updated using a proportional-integral (PI) law, which can provide a faster parameters update and automatically a faster convergence of error to zero. Even when the plant is subjected to external disturbances and inputs variations, the proposed FMRAC still can learn how to control the nonlinear plant and achieves asymptotic tracking of a stable reference model. The FMRAC performance is evaluated by a simulation study on 2-dof underwater planar manipulator. The simulation results demonstrate the controller tracking performance and its robustness.

Underwater manipulator control system

Each joint of manipulator are powered and driven by actuator that applies force or torque to cause motion of the links. A control system provides the actuator commands that move the manipulator and achieve the specified end-effector motion. These commands are based on the "control set-points" generated from the trajectory planner. The actual joint and/or end-effector positions and their derivatives are measured using sensor and feedback to the controller to correct the error.

Manipulator dynamic model

Fig. 1 illustrates the 2-dof underwater planar manipulator mounting on the vehicle. The coupled effect between manipulator and vehicle is neglected and the ROV is assumed stationary during manipulator moves. The motion of manipulator is limited to horizontal direction.

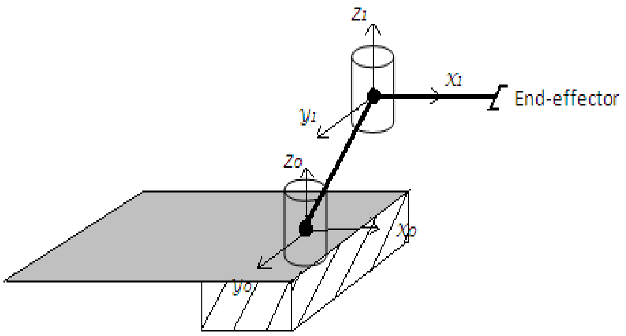

Fig. 1. 2-dof underwater planar manipulator on the ROV

a. Land-based manipulator

$$\mathrm{M}(\mathrm{q})\ddot{\mathrm{q}} + \mathrm{C}(\mathrm{q},\dot{\mathrm{q}})\dot{\mathrm{q}} + \mathrm{F_g}(\mathrm{q}) = \mathrm{u} \qquad (1)$$

where q is the n x 1 joint angle vector, $M(q)$ is the $n \times n$ inertia matrix, $C(q,\dot{q})$ is the $n \times n$ coriolis and centripetal matrix, F_g is the gravity factor and u is the input torque.

b. Underwater manipulator

Hydrostatics

In static analysis of underwater bodies, both the *gravitational force* acting on the body mass and *buoyancy force* must be considered. Archimedes's principle states that the buoyant force is equal to the weight of the fluid displaced. The equations annotate these forces as:

$$\begin{aligned} \mathrm{F_{buoyancy}} &= \rho\,\mathrm{V}\,\mathrm{g} \\ \mathrm{F_{gravity}} &= \mathrm{m}\,\mathrm{g} \\ \mathrm{F_{total}} &= \mathrm{F_{buoyancy}} - \mathrm{F_{gravity}} \end{aligned} \qquad (2)$$

V is the volume of the body of water, m is the link mass and g is the gravitational constant.

Hydrodynamics

Added mass is the effect of fluid inertia in the environment on a moving body. This is not a phenomena that extends to above water operations, however, the effect is vastly more significant subsea as the density of water is much more comparable to the density of the body of interest. The added mass coefficient is dependent on body geometry and motion. By approximating the manipulator as slow moving and which has 3 planes of symmetry as common for underwater vehicles the added mass will take a diagonal form of a 6×6 matrix. This will give the added mass the following form as per Fossen [11].

$$\mathrm{M_A} = \mathrm{M_A}^{\mathrm{T}} = -\mathrm{diag}\{\mathrm{X_u}, \mathrm{Y_v}, \mathrm{Z_w}, \mathrm{K_p}, \mathrm{M_q}, \mathrm{N_r}\} \qquad (3)$$

Drag acts in parallel with the flow velocity on the body and the drag force for each link is calculated as

$$\mathrm{F_{d(i)}} = \frac{\rho C_d A_s}{2}\int_0^l x|U_i(x)|U_i(x)dx \qquad (4)$$

C_d is the drag coefficient, A_s is the area surface, U(x) is the velocity normal to the link. The lift force which is caused by the shedding of vortices into the wake is always neglected. The dynamic equation of underwater manipulator becomes as follows:

$$\mathrm{M}(\mathrm{q})\ddot{\mathrm{q}} + \mathrm{C}(\mathrm{q},\dot{\mathrm{q}})\dot{\mathrm{q}} + \mathrm{F_g}(\mathrm{q}) - \mathrm{F_{buoy}} + \mathrm{F_d} + \mathrm{F_m} = \mathrm{u} \qquad (5)$$

$M(q)$ and $C(q,\dot{q})$ vary from the land-based manipulator because it has been included with added mass. F_{buoy} is the buoyancy factor and F_d is the drag force. The matrices of the dynamic equation for this manipulator are:

$$\mathrm{M}(\mathrm{q}) = \begin{bmatrix} l_2^2 m_{a2} + 2l_1 l_2 m_{a2} c_2 + l_1^2(m_{a1}+m_{a2}) & l_2^2 m_{a2} + l_1 l_2 m_{a2} c_2 \\ l_2^2 m_{a2} + l_1 l_2 m_{a2} c_2 & l_2^2 m_{a2} \end{bmatrix}$$

$$\mathrm{C}(\mathrm{q},\dot{\mathrm{q}}) = \begin{bmatrix} -m_{a2} l_1 l_2 s_2 \dot{q}_2 & -m_{a2} l_1 l_2 s_2 (\dot{q}_1 + \dot{q}_2) \\ m_{a2} l_1 l_2 s_2 \dot{q}_1 & 0 \end{bmatrix}$$

$$\mathrm{h}(\mathrm{q}) = \begin{bmatrix} (m_2 - \nabla_2) l_2 g c_{12} + (m_1 + m_2 - \nabla_1 - \nabla_2) l_1 g c_1 \\ (m_2 - \nabla_2) l_2 g c_{12} \end{bmatrix}$$

$$\mathrm{F_v} = \begin{bmatrix} k_{v1} & \dot{q}_1 \\ k_{v2} & \dot{q}_2 \end{bmatrix} \qquad \mathrm{F_c} = \begin{bmatrix} k_{c1} & \mathrm{sign}\,(\dot{q}_1) \\ k_{v2} & \mathrm{sign}\,(\dot{q}_2) \end{bmatrix} \qquad (6)$$

m_{a1} and m_{a2} represent the total mass of links 1 and 2 including added mass respectively. h is the total force of gravity and buoyancy ($F_g - F_{buoy}$). ∇ or ρV is the mass of water displaced by the link. The drag force values can be computed regarding to equation (4). $\mathrm{F_m} = \mathrm{F_v} + \mathrm{F_c}$ where F_v and F_c are the viscous and coulomb friction torques respectively. $c_i = cos\Theta$, $s_i = sin\Theta$, $c_{ij} = cos(\Theta_i + \Theta_j)$ and $s_{ij} = sin(\Theta_i + \Theta_j)$. Table 1 gives the parameters of both links. The hydrodynamics coefficient C_d is 1.1 and the water density ρ is selected as 1025 kg/m^3. The frictions coefficients are as follows: $\mathrm{k_{v2}} = \mathrm{k_{c2}} = 0.5$, $\mathrm{k_{v1}} =$

0.3 and $k_{c1} = 0.2$. l_1, r_1 and $m1$ are the length of link, radius of link and mass of link respectively.

Table 1- Parameters of links

Link 1 and 2 parameters	Value
l_1	0.543 m
l_2	0.337 m
r_1	0.075 m
r_2	0.075 m
m_1	30.0 kg
m_2	20.0 kg
m_{a1}	39.84 kg
m_{a2}	26.1 kg

The proposed FMRAC system

a. Structure of overall control system

In the literature, various of control schemes in a form of hybrid control structure for underwater manipulator have been researched and designed but not as widely as that of land-based manipulator. In this paper, a fuzzy logic approach with model reference adaptive control is suggested whereby the idea is firstly introduced by [8]. The ability of FMRAC has been proven before in some applications. In general, an adaptive control involves modifying the control law used by a controller to cope with the fact that the parameters of the system being controlled are slowly time-varying or uncertain. Fig. 2 ilustrates the block diagram of FMRAC. FMRAC can learn how to control the nonlinear plant and achieves asymptotic tracking of a stable reference model, even when the plant is subject to external disturbances and input variations.

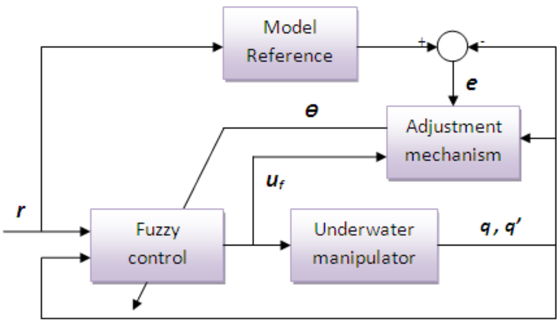

Fig. 2. FMRAC block diagram

e represents the model following error, ***r*** is reference signal, $\boldsymbol{\theta}$ is the controller parameter, $\boldsymbol{u_f}$ is the output controller and ***q,q'*** are the joints position and motion velocity respectively. In this case, the parameter of fuzzy controller will be updated by adjustment mechanism using PI law. PI law is used because of its fast parameter adaptation feature and fast convergence rate of the tracking error. A Lyapunov theory is used to ensure the stability of the system. Lyapunov theory is a primary method of testing the stability of nonlinear or linear system with uncertainty.

b. Structure of reference model

For reference model, a second order system is frequently applied. The parameters used are chosen properly according to the desired behavior that we want the system react. A standard second order reference model is given as:

$$G(s) = \frac{\omega_{n^2}}{s^2 + 2\xi\omega_n s + \omega_{n^2}} \qquad (7)$$

where $\xi\omega_n$ is called attenuation, ω_n is the undamped natural frequency and ξ represents the damping ratio of the system. The behavior of the system depends on the relative values of the ω_n and ξ. In this project, the value of ξ is set to 1, while the value of ω_n can be computed when settling time is set to 3 seconds. When $\zeta = 1$, the system is said to be critically damped. A critically damped system converges to zero faster than any other without oscillating. By assigning this value, the reference model transfer function in (7) becomes:

$$G_m(s) = \frac{1.78}{s^2 + 2.66s + 1.78} \qquad (8)$$

The reference model is usually represented in a form of state-space instead of transfer function. When the transfer function is converted into state-space, the value of matrix A_m, B_m and C_m are equal to:

$$A_m = \begin{bmatrix} 0 & 1 \\ -1.78 & -2.66 \end{bmatrix} \qquad B_m = \begin{bmatrix} 0 \\ 1.78 \end{bmatrix}$$

$$C_m = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

c. Structure of fuzzy adaptive control

Takagi-Sugeno fuzzy system is applied to design the adaptive controller. By using TS fuzzy system only a few rules is used for describing a highly nonlinear plant as compared to Mamdani fuzzy system. The adaptive controller to be designed is a multiple-input single-output (MISO) TS fuzzy system constituted by a set of IF-THEN fuzzy rules of the form [8].

$$R_k^i : If\ x_j\ is\ V_p^i\ Then\ u_{fi} = c_{k1}^i x_1 + .. + c_{kn}^i x_n + c_{kn+1}^i r_1 \qquad (9)$$

where $k=1,\dots,m_i$, m_i is the number of rules, x_j is the fuzzy input vector and the V_p^i are the fuzzy sets of inputs as shown in Fig. 3 where p=1,..,3.

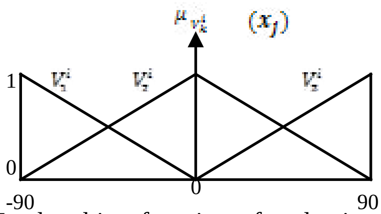

Fig. 3. Memberships functions for the input x_j of fuzzy controller

In this fuzzy controller, the following sets of rules are defined:

FMRAC1:

$If\ x_1\ is\ V_k^1$

$Then\ u_{f1} = c_{k1}^1 x_1 + c_{k2}^1 x_2 + c_{k3}^1 x_3 + c_{k4}^1 x_4 + c_{k5}^1 r_1$

FMRAC1:

$If\ x_3\ is\ V_k^2$

$Then\ u_{f2} = c_{k1}^2 x_1 + c_{k2}^2 x_2 + c_{k3}^2 x_3 + c_{k4}^2 x_4 + c_{k5}^2 r_1$

By using center-average defuzzifier, the output of the *i*th fuzzy controller can be inferred as follows:

$$u_{fi} = \frac{\sum_{k=1}^{m_i} \mu_k^i(v^i)\ \left(\sum_{j=1}^{n} c_{kj}^i x_j + c_{kn+1}^i r_i\right)}{\sum_{k=1}^{m_i} \mu_k^i\,(v^i)} \quad (10)$$

where $\mu_k^i(x_j)$ is the grade of membership of x_j in V_k^i. Only *j=1,3* are activated referring to q_1 and q_2. Each time, it is assumed that there exists at least one active rule. Equation (10) is simplified into the following compact form:

$$\mu f_i = \varepsilon_i \theta_i z_i \quad (11)$$

where

$$\varepsilon_i = \frac{1}{\sum_{k=1}^{m_i} \mu_k^i}\begin{bmatrix} \mu_1^i & \mu_2^i & \dots & \mu_{m_i}^i \end{bmatrix} \quad (12)$$

$$\theta_i = \begin{bmatrix} c_{11}^i & \dots & c_{1n+1}^i \\ \vdots & \dots & \vdots \\ c_{m_i 1}^i & \dots & c_{m_i n+1}^i \end{bmatrix} \quad (13)$$

$$z_i = [x^T \quad r_i]^T \quad (14)$$

ε_i is the *1x3* vector of the normalized strength**,** θ_i is the *3x5* parameters matrix and z_i is the *5x1* input vector. Therefore, the outputs for both fuzzy controllers are given by

$$\mu f_1 = \varepsilon_1 \theta_1 z_1 \quad (15)$$

$$\mu f_2 = \varepsilon_2 \theta_2 z_2 \quad (16)$$

The input vector $x^T = [x_1^T \quad x_2^T]$ which is $x_1^T = [q_1 \quad \dot{q}_1]$, $x_2^T = [q_2 \quad \dot{q}_2]$ and r_i is the reference input. The fuzzy controller parameters θ will be updated using the following proportional and integral (PI) law:

$$\theta_i = \varphi_i + \emptyset_i \quad (17)$$

where

$$\varphi_i = \gamma_{i1} b_{ci}^T P_i e_i \varepsilon_i^T z_i^T \quad (18)$$

$$\dot{\emptyset}_i = \gamma_{i2} b_{ci}^T P_i e_i \varepsilon_i^T z_i^T \quad (19)$$

$$\theta_i = \gamma_{i1} b_{ci}^T P_i e_i \varepsilon_i^T z_i^T + \gamma_{i2} \int_0^t b_{ci}^T P_i e_i \varepsilon_i^T z_i^T \quad (20)$$

$b_{ci}^T = [0 \ \dots . \quad 0 \quad 1]$, γ_{i1} and γ_{i2} are constants. The symmetric positive definite matrices P_i are determined from the following Lyapunov equation:

$$A_{m_i}^T P_i + P_i A_{m_i} = -Q_i \quad (21)$$

d. Stability

Lyapunov stability does not depend on testing the roots and eigenvalues or poles but primary concerned with testing system behavior. It is a primary method of testing the stability of nonlinear or linear systems with uncertainty or reliability problem. The system is mostly stable if the Lyapunov function *V* fulfills some conditions. The conditions are:

i. *V* is positive definite function
ii. $\dot{V}$ is negative definite function
iii. *V* must be radially unbounded

In this case, the Lyapunov function candidate is considered as which is proposed by [8]:

$$V = \sum_{i=1}^{p} V_i \quad (22)$$

with

$$V_i = \frac{\gamma_{i2}}{2 b_{ii}(x)} e_i^T P_i e_i + \frac{1}{2} tr\left(\widetilde{\emptyset}_i^T \widetilde{\emptyset}_i\right) \quad (23)$$

This function is already verified to fulfill the conditions in [8]. $\widetilde{\emptyset}_i$ is the controller parameter estimation error. The matrices of $P_{1,2}$ is determined from (21) when the value of $Q_{1,2} = \begin{bmatrix} 15 & 0 \\ 0 & 5 \end{bmatrix}$ is taken. The positive definite matrices P_i and Q_i are guaranteed exist since A_{m_i} are Hurtwiz matrices. $P_{1,2} = \begin{bmatrix} 15.72 & 4.21 \\ 4.21 & 2.51 \end{bmatrix}$. In Matlab, P can be found using lyap.m by specifying A and Q.

Simulation analysis

The objective of controlling manipulators is to maintain the accuracy of the end-effector position. In industry, two classes of accuracy are considered which is trajectory accuracy and end point accuracy. Generally, a trajectory accurate controller is concerned with the accuracy of the end-effector continuously along a pre-designated trajectory within some margin of error and within a specific time period. While in the later class, the two end points of the robot are of most concern with less of an emphasis on the trajectory that it follows. The choice between these two classes depends upon the application; one application may need end point accuracy while another needs trajectory accuracy. This paper will consider the trajectory accuracy because the accurate trajectory can also be considered as end point accuracy while vice versa is not true.

2-dof underwater planar manipulator is used to verify the performance of FMRAC. As in (5), the dynamic equation of this manipulator is:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + F_g(q) - F_{buoy} + F_d = u \quad (24)$$

where $q = [\,q_1 \quad q_2]$ is vector of the joint coordinates. In adjustment mechanism, the values of gains $\gamma_{11} = \gamma_{12} = \gamma_{i1} = \gamma_{i2} = 300$ are chosen. Consider the variation of q_i is in the interval [-pi/2 pi/2]. For simulations, the disturbances are considered as:

$$d = [20\sin(t)\ \ 20\sin(t)]$$

Fig. 4 and 5 show a good tracking of both joints to follow the desired and reference model trajectories when the desired q_1 and q_2 are set as pi/2 and pi/3 respectively. When the trajectories are changing after some periods, the joints also have the capability to follow the changes fastly. In the last analysis, disturbances are included to represent the current in the form of sine signal continuously. The errors can be considered converge to zero because the ripple is very small. Fig. 10 verifies that even though the mass change, the response is not affected.

Conclusion

The performance of the FMRAC controlled ground-fixed-underwater manipulator is applied and investigated in terms of servo tracking (joint trajectories). The simulation results demonstrate that the actual joint trajectories of the manipulator for both joints follow asymptotically the desired trajectories defined by the reference model. Despite of the added hydrostatic and hydrodynamic effect in the manipulator dynamics, the servo tracking performance of the chosen controller scheme is proven to be good and satisfactory. The elegant advantage of the hybrid controller scheme which comprises of Takagi-Sugeno-fuzzification-type-fuzzy controller merged with MRAC which equipped with PI adjustment mechanism is clearly demonstrated.

Acknowledgement

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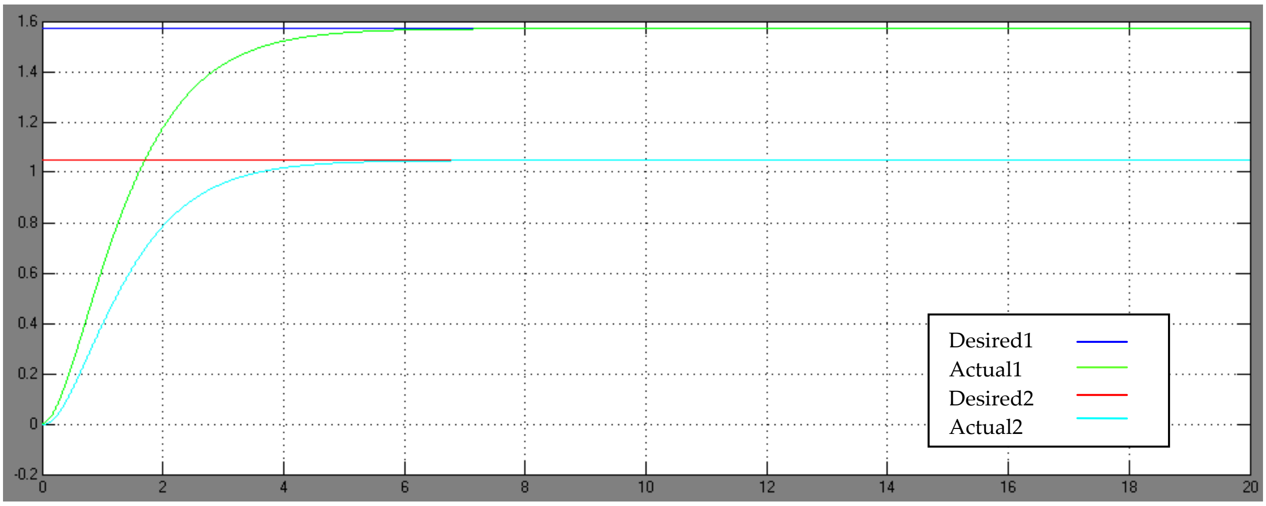

Fig. 4. Desired and actual trajectories of joint 1 and 2

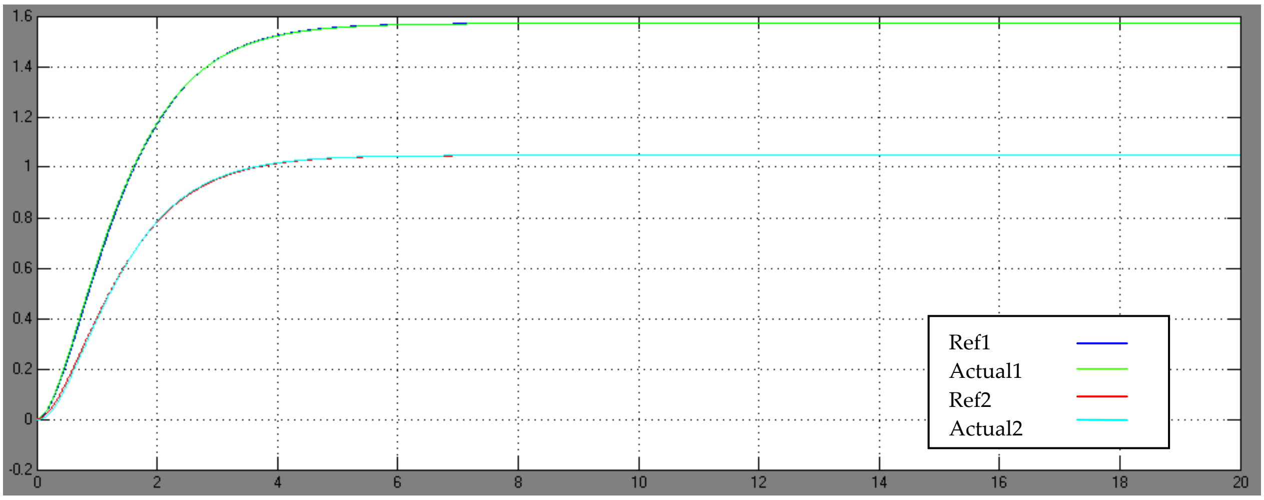

Fig. 5. Reference and actual trajectories of joint 1 and 2

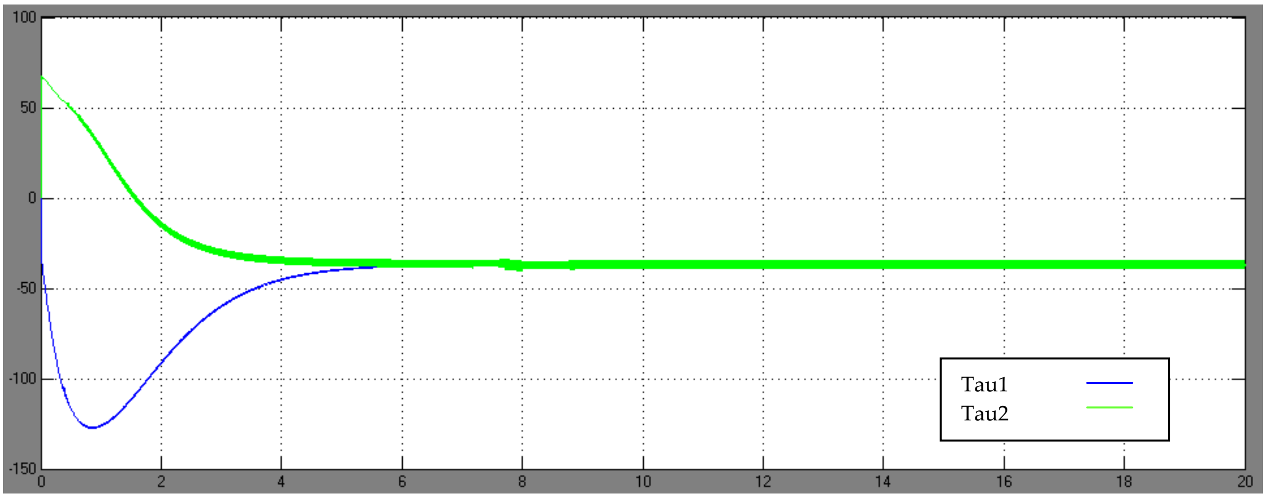

Fig. 6. Torques of joint 1 and 2

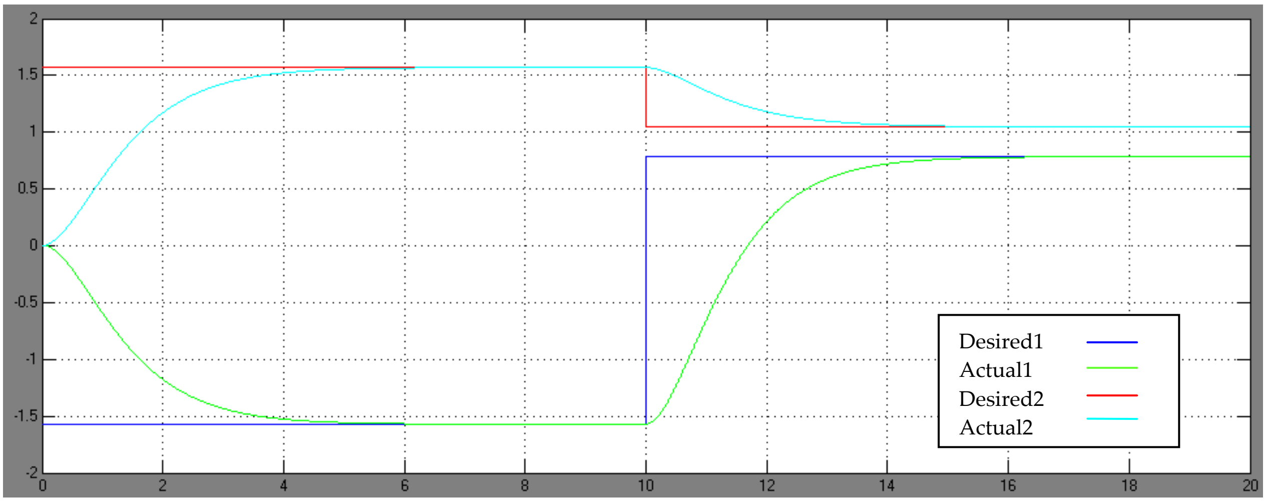

Fig. 7. Desired and actual trajectories of joint 1 and 2 when desired trajectories changing

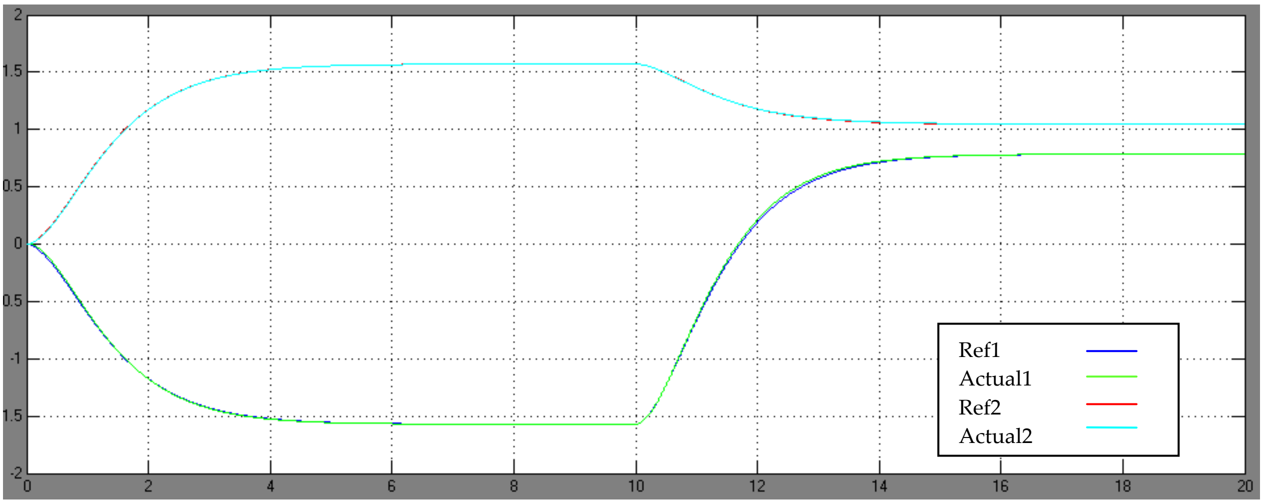

Fig. 8. Reference and actual trajectories of joint 1 and 2 when desired trajectories changing

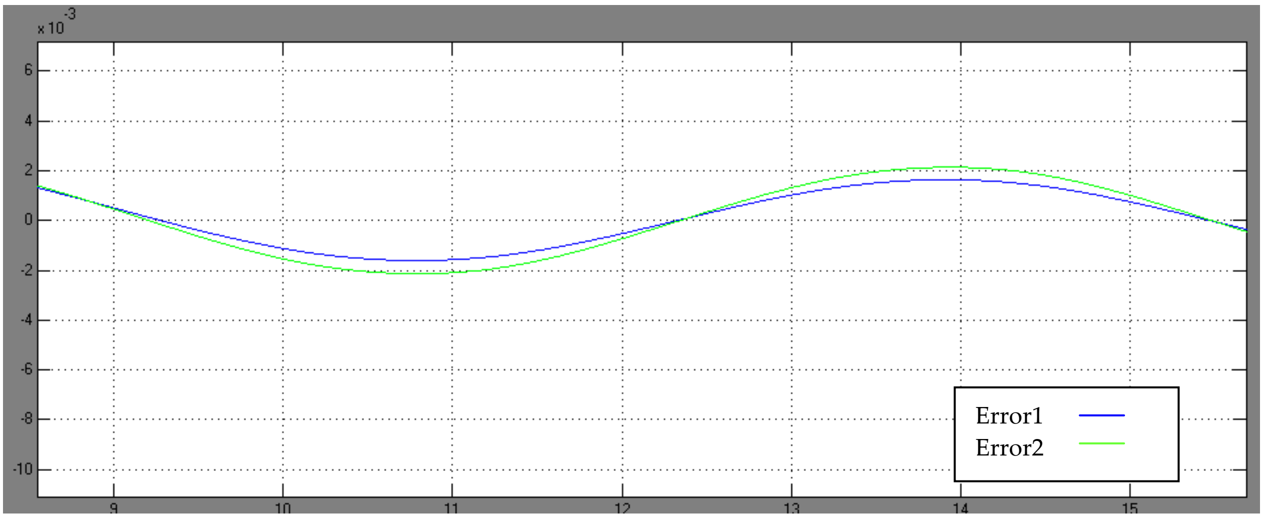

Fig. 9. Zoomed errors of joint 1 and 2 when disturbance is included

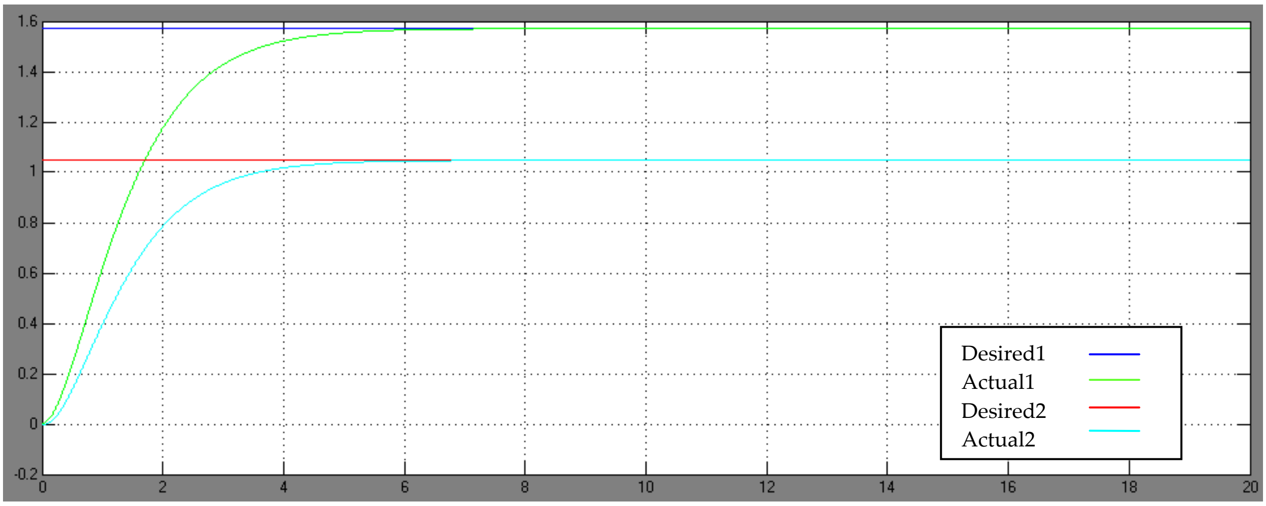

Fig. 10. Desired and actual trajectories of joint 1 and 2 when mass change